Experimental Validation of Swarm Array Results using Mars Cube One (MarCO) A,B Downlink Signals

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Abstract— **In this paper, we investigate the feasibility of calibrating an orbiting phaased array composed of CubeSat class spacecraft together with a larger reference (or "chief") spacecraft, comprising an overall Swarm Array. Considered as an analog to the Deep Space Network (DSN) Uplink Arraying problem [1], a spaceborne Swarm Array that can potentially deliver comparable or even greater operational performance than large monolithic spacecraft (such as increased data-rates for telecommunications, or greater baselines for improved spatial resolution), thus increasing future mission capability but with significantly enhanced flexibility, evolvability and robustness.**

TABLE OF CONTENTS

1. INTRODUCTION

Two CubeSats, designated as Mars Cube One (MarCO) A and B, were launched together with the InSight spacecraft on May 5th, 2018, and accompanied the InSight lander on its journey to Mars. As reported in a previous paper [2], the combined performance of a Swarm Array consisting of ~30 MarCO class CubeSats configured as an orbiting phased-array can achieve MRO (Mars Reconnaissance Orbiter) level performance, and with 95 MarCO CubeSats a Swarm Array could potentially achieve ten times MRO-level performance, if phase-coherence can be maintained.

The Swarm Array concept is illustrated in Figure 1, which shows a future Swarm Array in orbit around Mars, transmitting coherently phased signals back to Earth. Swarms of low-cost SmallSats can deliver a comparable or greater mission capability than large monolithic spacecraft, but with significantly enhanced flexibility (adaptability, scalability, evolvability, and maintainability) and robustness (reliability, survivability, and fault-tolerance).

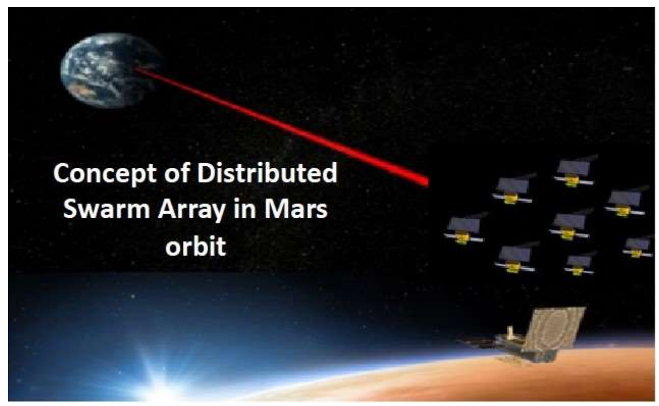

Figure 1. Conceptual diagram of Swarm Array transmitter in orbit around Mars

Our previous research [1] investigated the feasibility of a wideband Swarm Array in Martian orbit to address future communications requirements. Since the uplink arraying technology from the Deep Space Network (DSN) to a target in space is well developed, and has been operating reliably for many years, our study considers the problem of the downlink from a spaceborne swarm array as the dual of the DSN uplink arraying problem. We assumed the swarm array elements to be CubeSat-sized spacecraft, similar to MarCO. The main conclusion of the study was that a high data rate downlink swarm array at Mars is feasible, and that approximately 30 MarCO CubeSat class configured as a Swram Array could achieve MRO-level performance, whereas 95 MarCO CubeSats could ideally achieve ten times MRO-level performance.

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A conceptual model of the Swarm Array is shown in Fig. 2. This model was used to generate the three-dimensional orbital dynamics of Fig. 3, both from the viewpoint of a "chief" spacecraft and the apparent view from Earth, over a timescale of days.

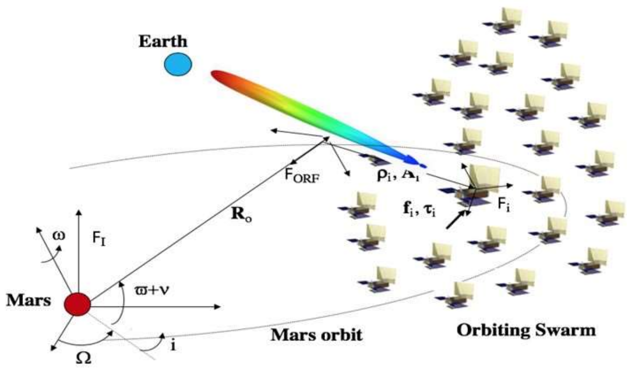

Fig. 2. Three-dimensional model of Swarm Array geometry.

The simulated orbital trajectories of the Swarm array are shown in Figures 3 a, b and Figure 4a, where Fig. 3a represents the view from the chief (or reference) spacecraft, Fig 3b is the earth-view and Fig. 4a is the projected distance along the line-of-sight from the ground to the Swarm Array over two days, showing that inter-element spacing varies sinusoidally in a nominal steady-state orbit.

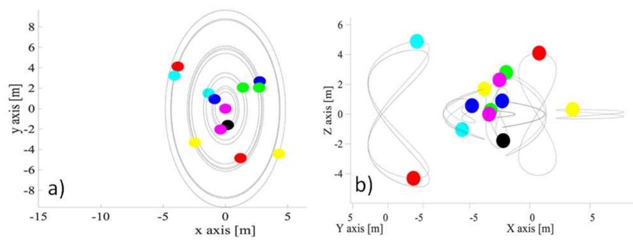

Figure 3. Swarm Array orbital trajectories: a) viewed from the chief spaceraft; b) viewed from the Earth.

Analysis of the data in Fig. 4a indicates that over short timescales of minutes, the relative delay between swarm elements remains nearly constant, with only a small quadratic (and possibly higher order) component. This observation will be used in the signal processing analysis to validate the model for measuring and predicting relative phase, in order to calibrate the Swarm Array and keep it phased up even as the distance between array elements changes with time.

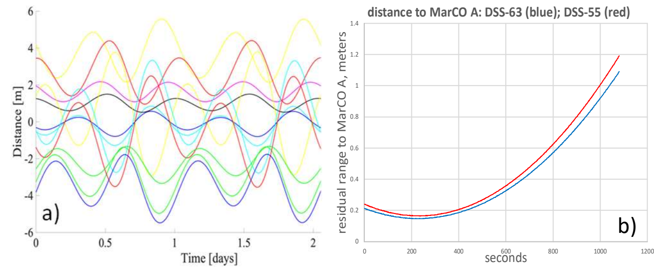

Figure 4. a) Projected distance along the array beam line-of-sight; b) Madrid antenna range from MarCO A, with linear trend removed, showing approximately quadratic behavior on a short time-scale.

For comparison, the range between MarCO A and two of the Madrid antenna elements (DSS-63 and DSS-55) has been plotted in Figure 4b over the time-interval of the data. Linear trends have been subtracted out to reveal the higher order components, since orbital dynamics are typically known well enough to be predicted a priori, leaving only small residual components that have to be estimated in real-time. It can be seen that the residual range appears to be quadratic over the timescale of the data, similar to the maximum rate-of-change near the peaks of the projected distance from the Swarm Array along the line-of-sight, that must be removed to enable coherent comining of the transmitted carriers at the target, as described in [1].

Based on these observations, we postulate that earth-rotation causes qualitatively similar range variations of the residual antenna phase-centers as would be expected near the most challenging parts of the Swarm Array orbit, as shown in Fig. 3c. The time-scale for the Swarm Array is periodic on a time-scale of about half a day, whereas the full-cycle variation of the Madrid antenna distances are periodic on a time-scale of one day, hence the results obtained here should be scaled to account for the different time-scales.

2. Data Acquisition at the Madrid Antenna Complex

Three deep-space antennas of the Madrid Deep Space Network (DSN) complex recorded downlink data from MarCO A/B simultaneously on Day-of-Year 330 (DOY-330) of 2018, and these data were used for the analysis reported in this paper. Six sets of complex baseband data were recorded on a wideband high-speed Open-Loop Recorder (OLR) of JPL's Radio Science group between 19:20 and 20:00 hours on DOY-330, and processed to determine the feasibility of phasing up the array using real spacecraft data obtained from deep space, generated by MarCO A/B's on-board transmitters with characteristic phase-noise and trajectory dynamics automatically embedded in the received signals. The data consisted of an 18-minute segment of two-way transmission from MarCO A recorded at 250 kHz sampling rate when the on-board oscillator was locked to an uplinked X-band reference signal, and a 24-minute segment where both MarCO A and B oscillators were free-running in one-way mode. However, after examining the data only the 18 minute two-way data was analyzed, because the one-way data was of relatively poor quality and also contained numerous signal drop-outs.

3. SIGNAL PROCESSING RESULTS

Two-way MarCO-A downlink data was recorded by the Radio Science Group's OLR, at each of three DSN Madrid stations designated as DSS-63/55/54. Signal processing algorithms were developed to process the data, and it was shown that accurate phase-calibration can be obtained in a few seconds, then used to predict future phase in order to maintain phase-coherence for the three antennas, which can also be viewed as proxies for a simulated Swarm Array due to reciprocity. In other words, reciprocity implies that a single spacecraft antenna in the vicinity of Mars (i.e. MarCO A) transmitting a signal to a cluster of three antennas on the ground rotating with the Earth's surface, is similar to a single ground-based antenna transmitting a signal to a Swarm Array in orbit around Mars.

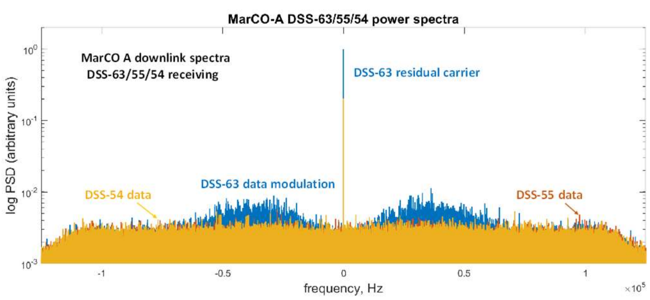

FIGURE 5. Power spectra of MarCO data collected from three Madrid antennas: DSS-63/55/54. Note the significant residual carrier, which can be used to estimate carrier phase.

The power spectra of MarCO A signals received by DSS-63/55/54 in the Madrid complex are shown in Fig. 5 obtained with a 250 kHz OLR sampling rate, showing both residual carriers an data modulation. Figure 6 a) is a zoomed view showing significant group Doppler and differential Doppler frequency profiles in the residual carriers roughly 18 Hz below center; and b) shows counter-rotated and nominally centered spectra used for analysis, showing chirp characteristics as the signal frequency changes slowly with time. Note that the residual carrier power in the 70m diameter antenna, DSS-63, is roughly a factor of 4 (or 6 dB) higher than the power in the two 34 meter antennas, DSS-54/55, as expected due to the greater aperture.

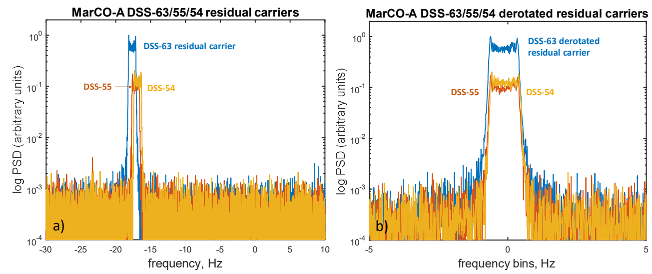

Fig. 6. Expanded views of power spectra of MarCO data collected from three Madrid antennas: DSS-63/55/54. a) view of residual carrier near the nominal center frequency showing significant Doppler; b) counter-rotated and centered spectra.

The counter-rotated residual carrier data were filtered to remove noise and interfering modulation components, and complex-downconverted to nominal baseband resulting in relatively clean in-phase (blue) and quadrature (red) signal components from all three antennas, as shown in Fig. 7. Note that the amplitude of the signal from the 70 m antenna is roughly twice as great (and less noisy) as the amplitudes from the 34 m antennas, hence the power is a factor of 4 greater, consistent with the previously observed power spectra.

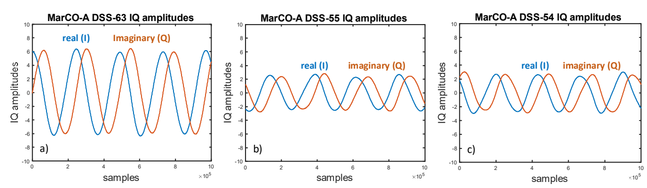

Fig. 7. In-phase and quadrature signal components from the three Madrid antennas: a) DSS-63; b) DSS-55; c) DSS-54.

The absolute phase trajectory of each antenna's signal was computed via the MATLAB atan2 function by inputting the in-phase and quadrature (IQ) components for each sample, and unwrapping the resulting sequences to obtain absolute phase, as shown in Figure 8a for all three signals. The phase trajectories, which are proportional to range, are seen to be roughly parabolic as expected from the dynamics described earlier.

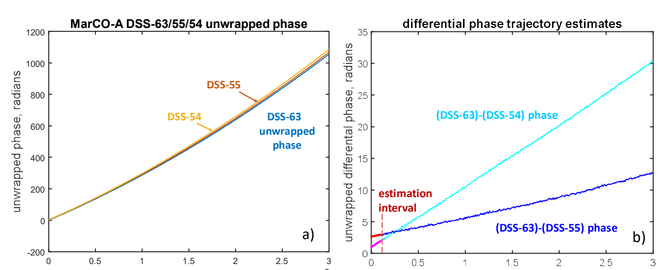

Fig. 8. a) Unwrapped phase trajectories for all three Madrid antennas, DSS-63/55/54; b) differential phase trajectories and estimates based on the first 4 seconds of data.

A total of thirty million (3×10^7) samples were used in this analysis, corresponding to 120 seconds of real-time data sampled at 250,000 samples per second. Since phasing of the array can be accomplished by designating a reference array element, typically the "chief" spacecraft that has the processing power to coordinate the entire swarm, it is sufficient to match the phase of each swarm element to a single reference antenna in order to phase up the array, after accounting for differences in range along the line-of-sight [1]. Hence it is sufficient to measure the differential phase between the reference transmitter and each element of the swarm. Following this reasoning, the 70 m antenna at DSS-63 was designated as the reference antenna (proxy for the chief spacecraft), and the phase difference between this and the other two antennas was computed, resulting in the difference-trajectories shown in Fig. 8b. Whereas the absolute phase changes by about 11,000 radians during this time, as can be seen in Fig. 6a, the relative phase changes by roughly 30 radians or less for both trajectories, as shown in Fig. 8b. It is also apparent that the difference phase trajectories are mostly linear, with possibly a small second-order (quadratic) component.

Based on these observations, a linear fitting algorithm was employed to estimate the phase trajectory coefficients based on the first 1 million samples (corresponding to 4 seconds of data), as shown by the red and magenta lines at the beginning of each differential phase trajectory in Fig. 8b. The estimated coefficients were then used to predict the differential phase for up to 120 seconds into the future.

It was observed that the difference phase trajectories were nearly linear with time, linear coefficients based on estimates over the first 4 seconds were used to generate the predicted difference-phase trajectories for the following 100 seconds, as shown in Figure 9a (dashed red and magenta lines). The accuracy of these linear predicts is quantified in Fig. 9b, which is the pairwise difference between the actual phase trajectory and the linear predicts constructed from the short-term estimates of the predict coefficients. It can be seen in Fig. 9b that the predicts are within 0.4 radians of the true phase for approximately 120 seconds with these data sets, suggesting that pairwise re-calibration once every 2 minutes should keep the ground-based antennas phased up continuously when operating as a phased-array transmitter. For a Swarm Array in Mars orbit the orbital dynamics will likely be different, hence these results would have to be scaled appropriately be scaled appropriately to account for different Doppler dynamics.

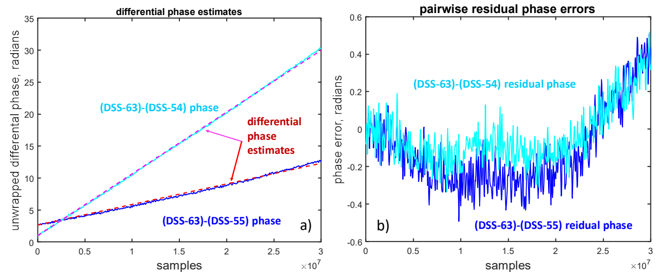

Figure 9. a) Differential phase estimates applied over a 100-second interval; b) residual phase error between true and predicted phase difference.

Next, the effectiveness of the predict-based algorithm for pairwise calibration of the Swarm Array is evaluated by applying the phase-difference predicts to the actual received signals, and combined to evaluate array performance. The received signals were counter-rotated using the predicted phases, and the in-phase components plotted in Fig. 10a to show reasonable alignment with the reference signal. It is apparent that the phases are reasonably well aligned via this predicts-based de-rotation, further suggesting that sample-amplitudes should add coherently to enable the formation of a phased array.

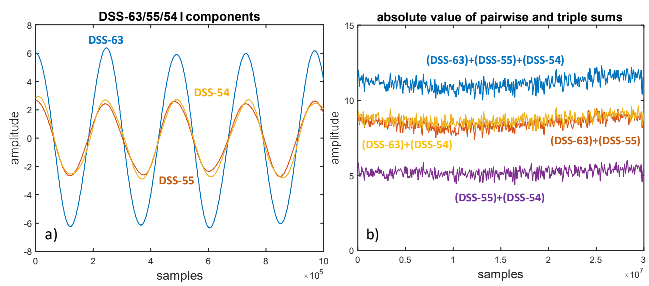

Fig. 10. a) predicts-based de-rotated signal amplitudes; b) pairwise sums and sum of all three signals, following predicts-based de-rotation.

This hypothesis was tested by combining the phase-compensated residual carriers. The pairwise sums of de-rotated DSS-63/55 and DSS-63/54 signals are shown in Fig. 10b, maintaining an amplitude of roughly 8 units, consistent with the amplitudes shown in Fig. 10a. The sum of all three signals is also shown, again demonstrating reasonable phasing of all three array elements over the entire 120-second data-set.

However, the implications for practical Swarm Array phasing is actually even more optimistic, because in a realistic application the array elements would radiate equal-amplitude signals, not randomly varying amplitudes as observed in Figure 10. The signal phase-trajectories will be adjusted according to the predicted difference-phase based on short-term phase measurements, but the transmitted signal amplitudes will be constant and typically equal in amplitude, without any significant amplitude fluctuations. This situation is illustrated in Figure 11, where equal unit-amplitude signals were added together, after being phase-compensated according to the residual phase error sequence shown in Figure 9b. With this more realistic model the signal amplitudes add nearly perfectly, yielding an ideal factor of 2 gain in amplitude for the two-antenna case, and factor of 3 amplitude gain for the three antenna case at the beginning of the 120 second interval where the residual phase error is close to zero radians.

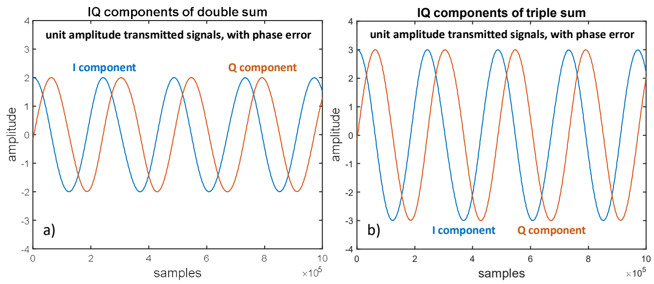

Fig. 11. a) IQ components of pairwise sum of unit-amplitude signals with residual phase errors applied; b) IQ components of three unit-amplitude signals with residual phase errors.

The linear gain of simulated 2- and 3-element arrays as a function of time over a single array element is shown in Fig. 12 a), and the corresponding gain in dB in Fig. 12b. Note that over the duration of this data-segment the 2- and 3-element array gain remains essentially constant at the theoretical levels of 6 and 9.5 dB respectively, exhibiting only a slight decrease in gain towards the end of the 120 second data-segment. Since the Swarm Array exhibits an orbital cycle in roughly half a day, whereas the motion of the Madrid antennas appear to have a period of one day when viewed from MarCO A, these proxy results should be scaled by a factor of two or so when translating them to the Martian Swarm Array.

However, since orbital trajectory knowledge was not used in this model, rather the estimates of the linear coefficients were based entirely on real-time data, it is reasonable to expect that even longer predict-based calibration can be achieved if the orbital trajectory information is incorporated into the phase-trajectory predicts, and if in addition higher-order coefficients are also employed to extend the calibration interval. These additional considerations are the subject of future research aimed at developing more accurate models of Swarm Array phase trajectories, and algorithms for calibrating and monitoring the inter-element phase vectors required for efficient operation of orbiting Swarm Arrays.

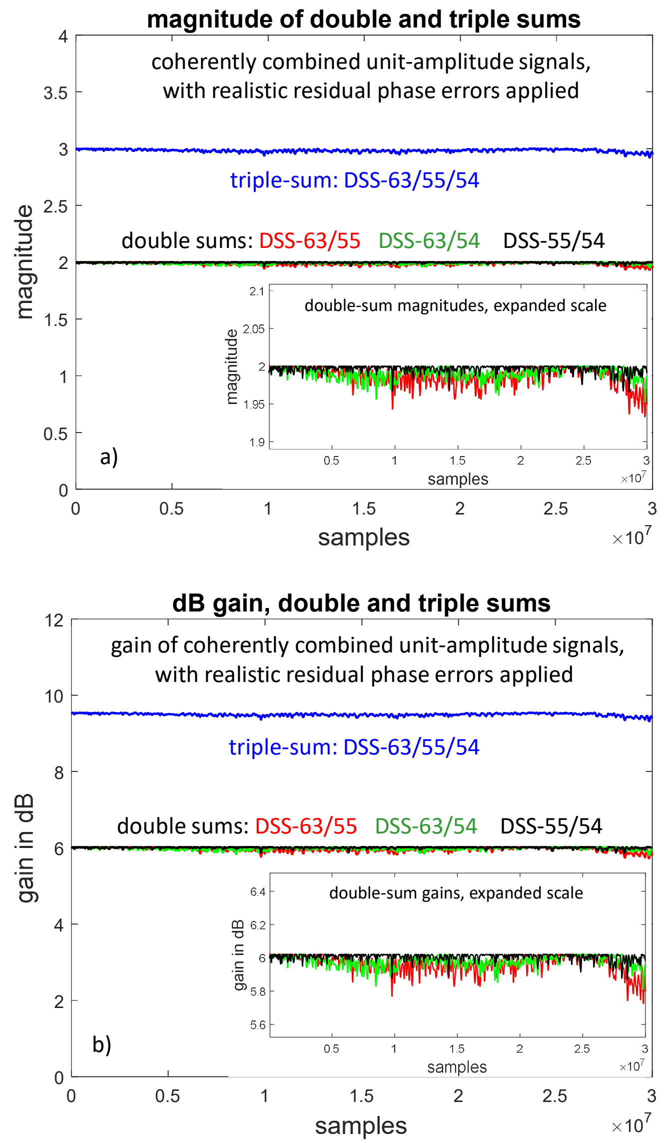

Fig. 12. Simulated combined Swarm Array signals incorporating residual phase errors obtained from MarCO A downlink data: a) magnitude of 2- and 3-element combined signals; b) dB gain of 2- and 3-element phased arrays over a single element, for the 120 second data interval.

4. Summary and Conclusions

In this paper, we made use of real two-way MarCO A data recorded at the Madrid DSN complex with three antennas, DSS-63/55/54, to simulate phase-trajectories comparable to what might be observed in a Swarm Array in orbit around Mars, to demonstrate that short-term observation of a test signal can be used to calibrate the array in real-time, potentially lasting 120 seconds before re-calibration to keep the array phased up.

The nominal 100 meter distances between the Madrid antennas are similar to inter-element spacing in a Swarm Array, hence these antennas rotating with the

Earth's surface were considered as proxies for the Swarm Array elements, potentially in orbit around Mars. The transmission from MarCO A can be viewed as a reference signal transmitted from the ground to help calibrate the array. It was shown that over short intervals of minutes, differential phase (hence relative distance) between antenna elements remained nearly linear hence a simple linear model could be used to predict future behavior accurately up to approximately 120 seconds. The measured phase trajectories were then used to simulate Swarm Array signals transmitted toward Earth as a phased array, and it was shown that phase calibration could be maintained via linear predicts for 120 seconds without significant loss in array gain for 2- and 3-element arrays. It is anticipated that even longer intervals may be possible in the future by incorporating known orbital dynamics into the predicts, and by estimating quadratic and higher-order coefficients to extend the validity of the stimates, but these topics remains the subject of future work.

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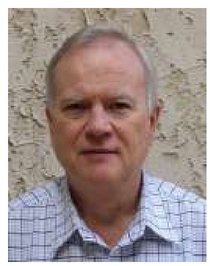
BIOGRAPHY



Victor Vilnrotter *(M'79, SM'02) received his Ph.D. in electrical engineering and communications theory from the University of Southern California in 1978. He joined the Jet Propulsion Laboratory, Pasadena, Calif., in 1979, where he is a Principal Engineer in the Communications Architectures and Research section. His research interests include electronic compensation of large antennas with focal-plane arrays, adaptive combining algorithms for antenna arrays, optical communications through atmospheric turbulence, the application of quantum communications to deep-space optical links, and the development of uplink array calibration and tracking technologies. He has published extensively in conferences and refereed journals, received numerous NASA awards for technical innovations, and a NASA Exceptional Service award for contributions to deep-space communications.*

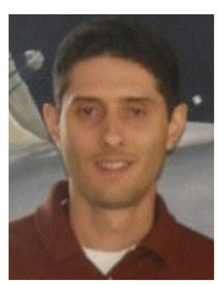
Marco Quadrelli *is an internationally renowned expert in modeling for dynamics and control of complex space systems. He has a Masters Degree in Aeronautics and Astronautics from MIT and a PhD in Aerospace Engineering from Georgia Tech. He was a visiting scientist at the Harvard-Smithsonian Center for Astrophysics, and a lecturer at the Caltech Graduate Aeronautical Laboratories. After joining NASA JPL in 1997 he has contributed to a number of flight projects including the Cassini---Huygens Probe, Deep Space One, the Mars Aerobot Test Program, the Mars Exploration Rovers, the*

Space Interferometry Mission, the Autonomous Rendezvous Experiment, and the Mars Science Laboratory, among others. He has been the Attitude Control lead of the Jupiter Icy Moons Orbiter Project, and the Integrated Modeling Task Manager for the Laser Interferometer Space Antenna. He has led or participated in several independent research and development projects in the areas of computational micromechanics, dynamics and control of tethered space systems, formation flying, inflatable apertures, hypersonic entry, precision landing, flexible multibody dynamics, guidance, navigation and control of spacecraft swarms, terramechanics, and precision pointing for optical systems. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics, a NASA Institute of Advanced Concepts Fellow, and a Caltech/Keck Institute for Space Studies Fellow.

Richard E. Hodges received the B.S. degree from the University of Texas at Austin, the M.S. degree from California State University, Northridge and the Ph.D. degree from the University of California Los Angeles, all in electrical engineering. From 1978 to 1984, he was with the Hughes Aircraft Company Radar Systems Group, Culver City, CA, where he performed design and analysis of electronic scanned array antennas, bandpass radomes, radiating elements (slots, printed circuit radiators, polyrods, etc.), and RF feed networks. In 1984, he joined the Adams-Russell Microwave Products Division, Chatsworth, CA (now Rantec Microwave Systems) where he developed waveguide-fed slot antennas for military radar applications. From 1988 to 1992, he was with NASA's Jet Propulsion Laboratory, Pasadena, CA, where he developed reflector antenna analysis software for the Deep Space Network, and coupled Finite-Element/Integral Equation code for the Parallel Computational Electromagnetics group. From 1992 to 1997, he was with UCLA performing research on electromagnetic modeling of complex radiators mounted on arbitrarily shaped bodies using the Hybrid Electric/Magnetic Field Integral Equation method and also worked as a Consultant to industry. From 1997 to 2001, he was with Raytheon's Antenna/Nonmetallics Technology Center, McKinney, TX, where he was the Technical Lead on Raytheon's DARPA RECAP program, which resulted in development of the world's first decade bandwidth (10:1) electronic scanned array antenna. At Raytheon, he also worked on a military airborne radar reflector antenna design and space- based electronic scanned array research. In 2001, he returned to the Jet Propulsion Laboratory where he a Principal Engineer performing research and development on space-based antennas for radar and telecommunications. He was the Technical Group Supervisor of JPL's Spacecraft Antennas Group from 2002-2018 and Principal Investigator for numerous projects including the Integrated Solar Array and Reflectarray (ISARA) CubeSat project, the Mars Cube One (MarCO) reflectarray antenna, the Instrument Incubator Program that led to the SWOT radar interferometer antenna, etc. His research interests include spaceborne deployable reflectarray antennas, deployable reflectors, waveguide slot array antennas and 3D printed lens antennas.

Saptarshi Bandyopadhyay is a Robotics Technologist at the Jet Propulsion Laboratory, California Institute of Technology, where he develops novel algorithms for future multi-agent and swarm missions. He received his Ph.D. in Aerospace Engineering in 2016 from the University of Illinois at Urbana-Champaign, USA, where he specialized in probabilistic swarm guidance and distributed estimation. He earned his Bachelors and Masters degree in Aerospace Engineering in 2010 from the Indian Institute of Technology Bombay, India, where as an undergraduate, he co-founded and led the institute's student satellite project Pratham, which was launched into low Earth orbit in September 2016. His engineering expertise stems from a long-standing interest in the science underlying space missions, since winning the gold medal for India at the 9th International Astronomy Olympiad held in Ukraine in 2004. Saptarshi's current research interests include robotics, multi-agent systems and swarms, dynamics and controls, estimation theory, probability theory, and systems engineering. He has published more than 40 papers in journals and refereed conferences.

Sue Finley has been an employee of NASA's Jet Propulsion Laboratory (JPL) since January 1958, making her the longest-serving woman in NASA. Two days before Explorer 1 was launched, Finley began her career with the laboratory as a human computer, calculating rocket launch trajectories by hand. She now serves as a subsystem engineer for NASA's Deep Space Network (DSN). At JPL, she has participated in the exploration of the Moon, the Sun, all the planets, and other bodies in the Solar System.



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